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Improving Signal Reliability for Indoor Off-body Communications using Spatial Diversity at the Base Station

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Abstract—In this paper, we investigate the potential improvement in signal reliability for indoor off-body communications when using spatial diversity at the base station. In particular, we utilize two hypothetical indoor base stations operating at 5.8 GHz each featuring four antennas which are spaced at either half- or one-wavelength apart. Three on-body locations are considered along with four types of user movement. The cross-correlation between the received signal envelopes observed at each base station antenna element was calculated and found to be always less than 0.5. Selection, maximal ratio, and equal gain combining of the received signal has shown that the greatest improvement is obtained when the user is mobile, with a maximum diversity gain of 11.34 dB achievable when using a four branch receiver. To model the fading envelope obtained at the output of the virtual combiners, we use diversity specific, theoretical probability density functions for multi-branch receivers operating in Nakagami- m fading channels. It is shown that these equations provide an excellent fit to the measured channel data.

Index Terms—spatial diversity, off-body communications, cross correlation, diversity gain, base station, antenna spacing.

I. INTRODUCTION

Off-body communications are a branch of body centric communications in which one or more wireless devices situated on the body communicate with a local transceiver or base station in a different physical location. In off-body communications channels, variations in the received signal occur due to body shadowing, movement of body parts, strong reflections from nearby objects and scattering from the body and surrounding environment [1]. These factors may degrade the quality of the radio link and reduce the overall signal reliability [2].

One possible method to mitigate these deleterious effects is to employ a spatial diversity configuration at the receiver. The key concept of spatial diversity is to combine multiple signals transmitted over different propagation paths with the aim of reducing the impact of deep fades. A fundamental issue in the successful implementation of spatial diversity techniques is that of antenna spacing, since the performance is influenced by correlation of the signals between the antenna elements. If the antenna elements are uncorrelated and subject to received signals with comparable mean levels, then employing spatial diversity at the receiver should provide a higher signal-to-noise ratio (SNR) compared to the

case when only one antenna element is used. It is generally accepted that a spacing of half-wavelength ($\lambda/2$) is theoretically sufficient for most applications [3].

To date, there have been a number of studies which have investigated the benefits of spatial diversity techniques for in-body to on-body [4, 5], on-body [6], off-body [7], and body-to-body [8] communications. What is common amongst these studies is that they have considered diversity systems which have utilized multiple antenna elements positioned on the human body. In this paper, we consider the issue of multiple antenna elements at receiver base stations which utilize different antenna spacing's for improving signal reliability in off-body communication systems. Furthermore we apply diversity specific analytical equations to model the fading obtained at the output of selection, maximal ratio and equal gain combiners operating in Nakagami- m fading channels.

This paper is organized as follows. Section II describes the experimental setup and measurement procedure. The data analysis methods including correlation, diversity gain, and the theoretical probability density functions (PDF) used to model the fading characteristics of the combined envelopes are explained in Section III. The cross-correlation between the antenna array elements and the diversity gain for each of the three combining techniques are presented in Section IV alongside the examples of the model fitting. Finally, Section V summaries the main findings and suggests some future work.

II. EXPERIMENTS

All of the experiments conducted in this study were carried out in Wireless Communication Laboratory situated on the second floor of the ECIT building at Queen's University Belfast in the United Kingdom. The building mainly consisted of metal studded dry wall with a metal tiled floor covered with polypropylene-fiber, rubber backed carpet tiles, and a metal ceiling with mineral fiber tiles and recessed louvered luminaries suspended 2.7 m above floor level. The lab contained a number of chairs, boxes, lab equipment and also desks constructed from medium density fiberboard. The lab was unoccupied for the duration of the experiments facilitating pedestrian free off-body channel measurements.

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The transmitter section of the radio channel measurement system consisted of an ML5805 transceiver, manufactured by RFMD, which was configured to transmit a continuous wave signal with a power level of +21 dBm at 5.8 GHz, within the Industrial, Scientific and Medical (ISM) band. The antennas used by both the transmitter and the hypothetical base station were +2.3 dBi, sleeve dipole antennas (Mobile Mark model PSKN3-24/55S). The transmit antenna was mounted parallel to the body surface of an adult male of height 1.83 m and mass 80 kg. The antenna was positioned at the three different body locations on the test subject: (a) the central chest region, at a height of 1.42 m, (b) the central waist region, at a height of 1.15 m, and (c) the right wrist region at a height of 0.98 m.

The receiver section (i.e. the hypothetical base station) of the radio-channel measurement system consisted of four identical sleeve dipole antennas and a Rohde & Schwarz ZVB-8 Vector Network Analyzer (VNA). The four antennas were connected to ports 1, 2, 3, and 4 of the VNA using calibrated low-loss coaxial cables. A calibration was performed prior to the experiments to eliminate the effects of the power amplifier and cable loss using a Rohde & Schwarz ZV-Z51 calibration unit. The antennas were aligned along a straight line with either an equal spacing of half-wavelength or one wavelength, i.e. a uniform linear array. The receiver array was mounted vertically on a non-conductive height adjustable stand at an elevation of 0.83 m above the floor level. Both the transmitter antenna and receiver antenna array were vertically polarized.

The VNA was configured as a sampling receiver, recording the b_1 wave quantity incident on ports 1, 2, 3, and 4 at a rate of 56 Hz. A number of different scenarios were considered in the experiments, these were: (1) stationary in line of sight (LOS), where the test subject faced the receiver antenna array such that the main signal path was directly illuminating the direction of maximum gain at the receiver; (2) stationary in non-line of sight (NLOS), where the test subject faced in the opposite direction to the receiver antenna array for maximum body shadowing conditions; (3) mobile LOS and (4) NLOS where the test subject walked towards and then away from the receiver antenna array in a straight line, respectively, and finally (5) random movement in LOS and (6) NLOS where the test subject walked randomly towards and then away from the receiver antenna array, respectively. Scenarios 1 and 2 were repeated at set points within the laboratory, starting at a point 1 m from the receiver antenna array and then repeating the measurements every 1 m (in a straight line) until reaching a point 9 m away. For scenarios 3 and 4, the test subject walked between these two bounding distances in LOS and NLOS respectively, repeating the individual measurement scenarios five times. For scenarios 5 and 6, this process was also repeated five times with the user walking randomly in LOS and NLOS respectively between the two distances.

III. DATA ANALYSIS

Prior to the diversity analysis at receiver base station, the cross-correlation between the signal envelopes observed at each antenna element was calculated. For a diversity scheme to be effective, each antenna element should receive statistically independent versions of the transmitted signal reducing the likelihood that all branches are experiencing correlated fading. As a relative figure of merit two signals are said to be suitably de-correlated if their cross-correlation coefficient is less than 0.7 [3]. The cross-correlation coefficient, ρ , between the fading envelopes r_1 (branch 1) and r_2 (branch 2) consisting of N samples may be represented by [9]

$$\rho = \frac{\sum_{i=1}^N [r_1(i) - \bar{r}_1][r_2(i) - \bar{r}_2]}{\sqrt{\sum_{i=1}^N [r_1(i) - \bar{r}_1]^2} \sqrt{\sum_{i=1}^N [r_2(i) - \bar{r}_2]^2}} \quad (1)$$

where i is the instantaneous sample value, and \bar{r}_1 and \bar{r}_2 are the respective means of the normalized signal envelopes. Normalization was performed by removing the global mean from the raw data in stationary scenarios and the local mean in the mobile scenarios. The local mean signal was calculated by averaging the signal over 100 samples.

In this paper we considered three commonly used diversity combining techniques namely selection, maximal ratio, and equal gain combining. Selection combining (SC) is a form of switched diversity, where the branch with the highest SNR is selected as an output. In practice, however, the branch with the largest signal plus noise contribution is used due to the difficulty in measuring SNR [3]. Thus for an array consisting of M branches, the SC output level R is

$$R_{SC} = \max(r_1, r_2, \dots, r_M) \quad (2)$$

where, r_M is the signal level observed in the M^{th} branch of the diversity receiver. In maximal ratio combining (MRC), the signals from all of the M branches are co-phased to provide coherent voltage addition and weighted according to their individual signal voltage to noise power ratio to provide the optimal SNR before being summated. If it is assumed that noise power is equal on all branches then the output level R of the M branches is

$$R_{MRC} = \sqrt{r_1^2 + r_2^2 + \dots + r_M^2}. \quad (3)$$

In certain cases, it is not convenient to provide the variable weighting capability required for MRC. In such cases, the branch weights are all set to unity and the signals from each branch are co-phased with unity gain to provide EGC diversity combining. Thus the EGC output level R is

$$R_{EGC} = \frac{r_1 + r_2 + \dots + r_M}{\sqrt{M}}. \quad (4)$$

The performance of each combining technique was evaluated in terms of its diversity gain, which is defined as the difference in signal level of the branch with the highest mean and that of the output of the diversity combiner for a given probability of signal reliability [9]. All diversity gain calculations in this paper were made at a signal reliability of 90%. To characterize the small-scale fading experienced at the output of the hypothetical base station, the theoretical PDFs for SC, EGC and MRC combiners operating in Nakagami- m fading channels [10] were fitted to the data. The m and Ω parameters were estimated using non-linear least squares routine programmed in MATLAB. Under the assumption of identical Nakagami- m fading conditions, equal noise power and independence between diversity branches Yacoub [10] has shown that the PDF, $p_{sc}(r)$, of the output of a selection combiner for M branches may be expressed as

$$p_{sc}(r) = \frac{2Mm^m r^{2m-1} \Gamma^{M-1}(m, mr^2/\Omega)}{\Omega^m \Gamma^M(m)} \exp\left(-m \frac{r^2}{\Omega}\right) \quad (5)$$

where, $\Gamma(m) = \int_0^\infty x^{m-1} \exp(-x) dx$ is the Gamma function and $\Gamma(a, b) = \int_0^b x^{a-1} \exp(-x) dx$ is the incomplete Gamma function. For an equal gain combiner with M branches operating in a Nakagami- m fading channel, the PDF $p_{EGC}(r)$ may be written as [10]

$$p_{EGC}(r) = \sqrt{\frac{2M}{\Omega}} \int_0^a \int_0^{a-u_M} \dots \int_0^{a-\sum_{i=3}^M u_i} g(u_2, \dots, u_M) du_2 \dots du_M \quad (6)$$

where, $g(u_2, \dots, u_M) = p(u_1 = a - \sum_{i=2}^M u_i) \prod_{i=2}^M p(u_i)$, $a = r\sqrt{2M/\Omega}$, and $p(u_i)$ is the density function of the normalized Nakagami- m envelope u_i , $u_i = r_i / \sqrt{\Omega/2}$ obtained as [10]

$$p(u_i) = \frac{m^m u_i^{2m-1}}{\Gamma(m) 2^{m-1}} \exp\left(-\frac{mu_i^2}{2}\right) \quad (7)$$

Similarly the PDF, $p_{MRC}(r)$, of the fading observed at the output of an M branch maximal ratio combiner operating in Nakagami- m may be written as [10]

$$p_{MRC}(r) = \frac{2m^{mM}}{\Gamma(mM)\sqrt{\Omega}} \left(\frac{r}{\sqrt{\Omega}}\right)^{2mM-1} \exp\left(-m \frac{r^2}{\Omega}\right). \quad (8)$$

IV. RESULTS

A. Cross-Correlation Coefficient

Across all scenarios, for both half- and one wavelength spacing and all three body positions, the estimated cross-correlation coefficients were always less than 0.5. For example, considering the two antenna separation distances at the receiver, when the test subject was stationary (scenarios 1 and 2), it was found that there was no significant difference between the two antenna spacing's. Here the cross-correlation coefficients were always in the range -0.37 and 0.44. As expected, for the scenarios when the test subject was mobile (scenarios 3-6), the majority of cross correlation values were closer to zero, with a range between -0.2 and 0.2 for both antenna separation distances at the base station. This was most likely due to the increased variability in the channel caused by movement and the associated increase in multipath interference from the surrounding environment. Assuming comparable mean signal levels, these results suggest that a receiver base station equipped with multiple antennas should provide sufficient dissemination of the transmitted signal to supply worthwhile diversity gain.

B. Diversity Gain

1) *Stationary User (scenarios 1 and 2)*: Table I shows the diversity gain statistics for each of the three combining schemes at 90% signal reliability in scenarios 1 and 2. As expected, the MRC combining scheme provided the highest overall diversity gains. For both the LOS and NLOS cases, the chest region had a greater gain for the half-wavelength spacing compared to the wavelength spacing. Here, the maximum diversity gain was 6.43 dB which was obtained for the chest positioned antenna in LOS with half-wavelength spacing at the base station, whereas the lowest overall prospective diversity gain was 0.36 dB, obtained for the waist antenna in LOS also with half-wavelength spacing.

2) *Mobile User (scenarios 3-6)*: Table I shows the mean diversity gain statistics for each of the three combining schemes at 90% signal reliability for scenarios 3-6. Please note that the diversity gain is averaged over the five repeated trials to improve the robustness of the diversity gain. Again, MRC provided the greatest diversity gain compared to the other diversity combining techniques. When the test subject was mobile, the diversity gain for NLOS conditions was slightly higher at all of the body locations compared to LOS conditions. The added variation in the off-body channel when the user was mobile, meant that the diversity gain was significantly improved compared to when the test subject was stationary. For example, in the case of the waist region at half-wavelength spacing, the maximum diversity gain for the stationary user was 4.08 dB and 4.98 dB in LOS and NLOS conditions, respectively, while the maximum diversity gain for mobile user was 10.15 dB and 10.94 dB. As we can see, the diversity gain improved by about 6 dB in both LOS and NLOS conditions for the mobile scenarios.

TABLE I. DIVERSITY GAIN FOR EACH OF THE THREE COMBINING TECHNIQUES FOR SCENARIOS 1 TO 6. IT SHOULD BE NOTED THAT FOR THE STATIONARY SCENARIOS (1 AND 2), THE DIVERSITY GAIN IS THE AVERAGE, CALCULATED FOR THE DATA COLLECTED FROM POINTS 1 M THROUGH TO 9 M.

Scenario		Diversity Scheme	Diversity Gain (dB)					
			Half-Wavelength Spacing			One Wavelength Spacing		
			Chest	Waist	Wrist	Chest	Waist	Wrist
Stationary User	1	SC	2.88	0.36	0.99	1.10	1.27	1.46
		EGC	5.87	3.59	4.22	3.92	3.89	4.13
		MRC	6.43	4.08	4.82	4.62	4.62	4.81
	2	SC	2.65	1.74	0.65	0.56	0.53	3.36
		EGC	5.48	4.13	3.87	3.01	3.30	5.86
		MRC	6.24	4.99	4.36	3.80	3.96	6.67
Mobile User	3	SC	5.86	4.31	5.77	7.35	7.26	7.79
		EGC	7.99	6.60	8.12	9.70	9.68	9.87
		MRC	8.92	7.45	8.95	10.55	10.47	10.84
	4	SC	7.94	7.71	6.23	7.40	8.56	7.95
		EGC	10.24	10.09	8.44	9.66	10.88	10.02
		MRC	11.10	10.94	9.34	10.58	11.74	11.01
	5	SC	7.87	7.18	5.97	7.10	7.24	7.04
		EGC	9.86	9.21	8.34	9.42	9.64	9.34
		MRC	10.81	10.15	9.09	10.29	10.45	10.19
	6	SC	8.27	7.34	6.91	7.97	7.93	8.13
		EGC	10.37	9.56	9.28	10.27	10.20	10.32
		MRC	11.34	10.47	10.10	11.16	11.08	11.26

Fig. 1 shows a 5 second excerpt of the measured received signal power at branch 1 (highest mean) while the user moved in NLOS with the transmitter on their chest during trial 5 of scenario 6 with a half-wavelength spacing between the antennas at the base station. The improvements in the received signal envelope achieved by using a four-branch MRC diversity combiner can be seen quite clearly. Here, not only is the mean signal level raised, but the greatest fade depths are reduced by around 10 dB. Fig. 2 shows the CDFs for scenario 6 (trial 5) with the transmitter mounted on the test subject's chest, waist and wrist with half-wavelength spacing at the base station. The branch with the highest mean signal level is also shown for comparison. It can be seen that MRC provided the highest diversity gains of 11.34, 10.47 and 10.10 dB for the chest, waist and wrist region respectively.

C. First-order Statistics of Diversity Combined Envelopes

As an example of the results of the model fitting, Table II shows the estimated m and Ω parameters for all of the potential diversity combining configurations for the waist region in scenario 4. In Table II, to improve the robustness of the parameter estimates, \bar{m} and $\bar{\Omega}$ are the mean parameter estimates of m and Ω averaged over the five the five repeated trials. As we can see from Table II, the m parameter estimates are quite close to 1. When the m parameter is equal to 1, the Nakagami- m PDF degenerates to the Rayleigh PDF. Therefore, this suggests that the small-scale fading conditions experienced in these experiments are similar to those for a diversity combiner operating in a Rayleigh fading environment.

Fig. 3 shows the empirical and theoretical PDFs for two- and four-branch diversity combined envelopes while the user was walking in straight line away from the receiver antenna array with the transmit antenna on the central waist region during trial 3 of scenario 4. In all of the combined channels, the respective theoretical first-order equation provided an excellent fit to all of the combined envelopes analyzed in this study. This suggests that theoretical PDFs for SC, EGC and MRC combiners operating in Nakagami fading conditions can be used to adequately describe first-order statistics for off-body systems operating at 5.8 GHz with multiple antennas at the base station.

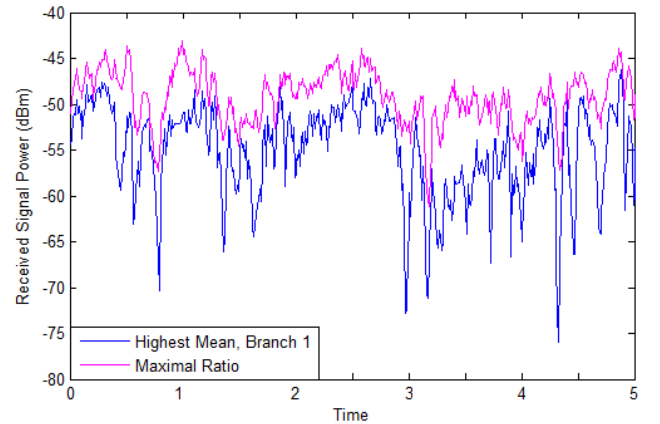


Fig. 1 Received signal power levels at branch 1 and the output of the hypothetical MRC combiner for the chest positioned antenna in scenario 6 with a half-wavelength antenna spacing at the base station.

TABLE II. ESTIMATED MODEL PARAMETERS FOR TWO-, THREE- AND FOUR-BRANCH DIVERSITY COMBINERS WITH HALF-WAVELENGTH ANTENNA SPACING AT THE BASE STATION AND THE TRANSMITTER AT THE WAIST REGION IN SCENARIO 4.

Number of Branches	Selection Combining		Equal Gain Combining		Maximum Ratio Combining	
	\bar{m}	$\bar{\Omega}$	\bar{m}	$\bar{\Omega}$	\bar{m}	$\bar{\Omega}$
Two-branch	1.03	0.67	1.02	0.63	1.02	0.50
Three-branch	0.93	0.54	0.97	0.43	0.94	0.33
Four-branch	0.90	0.47	0.95	0.32	0.92	0.25

V. CONCLUSION

The potential improvement in the received signal for off-body communications at 5.8 GHz using spatial diversity at base station has been investigated. For the experiments conducted here, the cross-correlation coefficient between the hypothetical base station antenna elements was always less than 0.5, irrespective of antenna spacing and body locations. It was also found that all three spatial diversity schemes achieved a worthwhile signal improvement in the majority of the scenarios considered in this study. It was particularly evident that spatial diversity will be useful for off-body channels at 5.8 GHz when the user is mobile. Finally, the first-order statistics of diversity combined envelopes have been presented and shown to provide a good match to the theoretical expressions for combiners operating in Nakagami- m fading channels. Future work will include diversity effects for off-body wireless communications when considering differing antenna polarizations and types.

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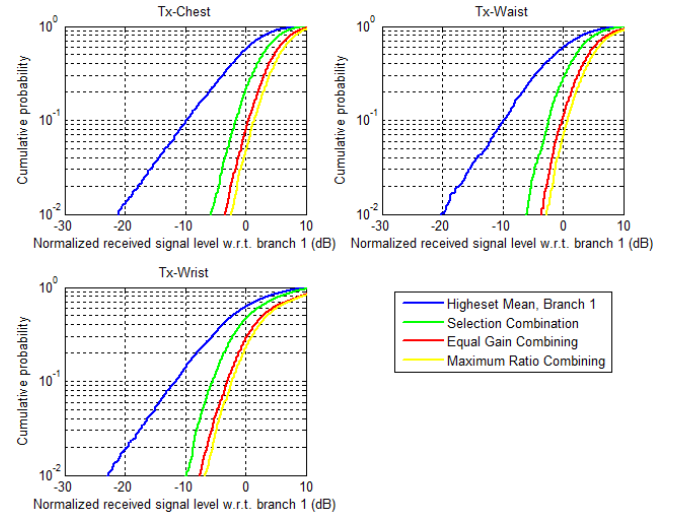


Fig. 2 Empirical CDFs of the output of the three combiners for the chest, waist, and wrist positioned antenna in scenario 6 with half-wavelength spacing at the base station at trial 5.

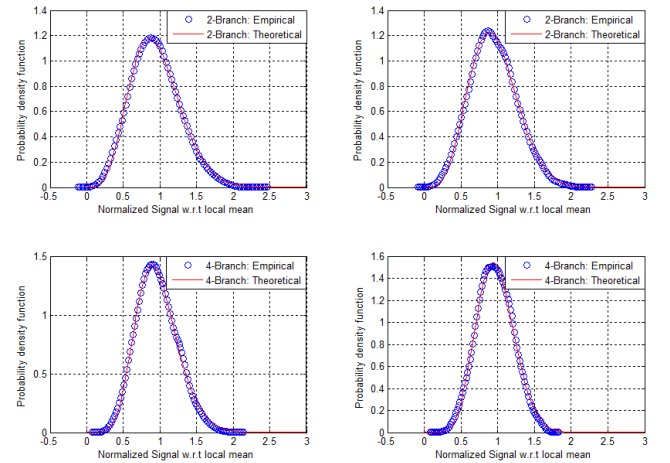


Fig. 3 Empirical and theoretical PDFs for two-, three-, and four-branch three (SC, EGC and MRC) diversity combined envelopes at trial 3 of scenario 4.